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13. ABSTRACT (Maximum 200 words)

The objective is to find out how saccadic eye movements (voluntary jumps of the eye) can be directed accurately to chosen targets within natural, patterned visual environments. An effective saccadic scanning mechanism must consist of: (1) a selective filer that determines which object serves as the saccadic target, and (2) a spatial-pooling mechanism that computes a single, precise saccadic landing position. Major findings were: (1) a single attentional filer serves both saccadic eye movements and perception; (2) attentional requirements of saccades are modest; (3) it is easier to divide attention between two widely-spaced targets than two closely-spaced targets; (4) the spatial-pooling process guides saccades to a central landing position within spatially-extended targets with a high degree of precision; (5) the central landing position is near the center of gravity; (6) the central landing position and the precision of the saccade depends on target size but not on spatial frequency content, contrast, or shape.

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ABSTRACT

The objective is to find out how saccadic eye movements (voluntary jumps of the eye) can be directed accurately to chosen targets within natural, patterned visual environments. An effective saccadic scanning mechanism must consist of: (1) a selective filter that determines which object serves as the saccadic target, and (2) a spatial-pooling mechanism that computes a single, precise saccadic landing position. Major findings were: (1) a single attentional filter serves both saccadic eye movements and perception; (2) attentional requirements of saccades are modest; (3) it is easier to divide attention between two widely-spaced targets than two closely-spaced targets; (4) the spatial-pooling process guides saccades to a central landing position within spatially-extended targets with a high degree of precision; (5) the central landing position is near the center of gravity; (6) the central landing position and the precision of the saccade depends on target size but not on spatial frequency content, contrast, or shape.

Objectives

The main objective of the work is to find out how saccadic eye movements (voluntary jumps of the eye) can be directed accurately to chosen targets within natural, patterned visual environments. The problem is not one of finding out which targets are chosen, but rather to understand the cognitive, visual and motor mechanisms that carry out the decisions. These mechanisms should ideally produce accurate saccadic patterns while at the same time making minimal demands on the cognitive resources otherwise needed to process the content of the visual scene. Natural patterned visual scenes have two characteristics that present a challenge to the mechanisms controlling saccades. First, in natural scenes the targets for saccades are spatially-extended objects. Second, in natural scenes the target objects are surrounded by extraneous objects in the background. An effective saccadic scanning mechanism must consist of: (1) a selective filter that determines which object or a portion of the visual scene serves as the saccadic target, and (2) a spatial-pooling mechanism that operates on information in a spatially-extended target to compute a single, precise saccadic landing position. Understanding the nature of the selective and pooling processes that work for human beings is significant for designing visual displays that support effective scanning, and for developing efficient procedures for the control of robotic visual systems which, like human beings, must guide sensors accurately to chosen targets within patterned scenes.

Status of effort

We have studied both the selective filter and the spatial pooling mechanism that guide saccades to chosen objects in natural visual scenes. Both processes work together remarkably well to ensure efficient scanning while at the same time imposing minimal cognitive load. Major findings are: (1) a single attentional filter serves both saccadic eye movements and perception, which means that the line of sight will, upon issuing a saccadic trigger signal, automatically be directed toward targets of interest; (2) attentional requirements of saccades are modest, freeing cognitive resources for other concurrent tasks and decisions; (3) it is easier to divide attention between two widely-spaced targets than two closely-spaced targets; (4) a spatial-pooling process guides saccades to a central landing position within spatially-extended targets with a surprisingly high degree of precision; (5) the central landing position is near (but not precisely at) the center of gravity of the pattern; (6) the locus of the central landing position and the precision of the saccade depends on target size but not on other target characteristics, such as spatial frequency content, contrast, or shape.

Relevance and applications

The results show that the oculomotor and cognitive systems interact with remarkable efficiency. For example, by linking saccadic target selection to the same attentional filter that serves perception it becomes unnecessary for observers to make a separate decision about where to aim the eye. The line of sight will automatically go to the attended region after a "go" signal is issued to trigger the movement. Moreover, the limitations on the attentional demands of saccades mean that considerable resources are available for selection of potential targets before the saccade is initiated. Finally, the finding of a highly-precise spatial pooling of attended regions means that observers need only select a target object; the precise endpoint of the saccade is determined automatically by lower-level visuomotor processes that do not require deliberate or cognitive intervention. Thus, the principle, employed by our visuomotor system, of using a two stage process -- target object selection followed by spatial pooling -- may prove of value in the design of artificial visual systems that must, as we do, aim sensors to selected targets in large visual scenes with minimal drain on available resources.

It is worthwhile noting that our information about saccadic scanning of natural visual scenes represents normal performance under optimal conditions, i.e., highly-visible displays inspected by highly-motivated and attentive observers. The performance under such conditions is remarkably good and is remarkably independent of the spatial structure of the visual scene (two notable exceptions: the impairment of precision with very large targets, see sections c and d, below; and the interference between closely-spaced targets, summarized in section b, below). These results serve as an important baseline for future work that would evaluate the expected deterioration of performance when optimal viewing conditions are unavailable, either because the visibility of the display or the cognitive state of the observer is impaired or because important visual targets are crowded together. Under such conditions, the spatial layout of the scene may become crucial in determining effective scanning.

Accomplishments and new findings

(a) Saccades and attention: These experiments explored the nature of the selective filter that guides saccades to chosen objects. The question was whether a single selective filter serves both perception and eye movements or whether the saccadic system employed its own, independent filter. If a shared selective filter is involved, then it would not be possible to prepare to look at one object while at the same time paying full perceptual attention to something else. We devised several "dual-task" experiments (concurrent measures of saccades and perception) requiring subjects to look at one target while identifying another. Considerable effort was devoted to development of dual-task methods that placed subjects' strategies under tight experimental control. We found that identification of a perceptual target (a randomly-chosen letter) was better at the saccadic goal than elsewhere. Surprisingly, it was possible to accurately identify a letter at a location other than the saccadic goal by increasing saccadic latency only 10-30%. These results show that saccadic programming does make demands on perceptual attention, but the atttentional demands are modest. To explain the results, we proposed that attention is not involved in saccadic programming until shortly before saccadic execution, and that it is at this time that the spatial parameters of the saccade are determined. One way to implement this process would by involving two systems, one that determines the saccadic goal (controlled by means of selective attention) and another that triggers the saccade. By setting the saccadic trigger to launch the saccade in response to the attentional shift, scanning would be both rapid and accurate while at the same time minimizing the need for time-consuming "on-line" decisions about when and where to aim the eye. (Kowler, Anderson, Dosher, and Blaser, 1995).

(b) Attentional interference: We performed a perceptual version of the experiment described above. Instead of looking at one target and trying to identify another, we asked subjects to identify two targets in a circular display (rad 4 deg) of 24 letters (Figure 1A). The objective was to measure the size of an 'attentional window', i.e., the region over which information can be acquired in a single attentional glimpse. The expected outcome was that it should be easy to identify a pair of letters so close to one another that they would fall within the same attentional window. By finding how performance declines with increasing separation, it would be possible to estimate the size of the window.

The experimental sequence (Fig. 1B) consisted of a pre-trial frame, pre-mask (500 msec), critical display frame containing the target letter (100, 200 or 300 msec) and a post-mask (500 msec). The locations of the target letters were indicated either by color cues present in (1) all frames or (2) the pre-trial frame only, or by numeral cues present in the pre-trial frame. Different types of cues were tested to ensure that

the results were not due to sensory attributes of the display but to the attentional requirements.

Contrary to expectations, target identification improved with increasing target separation. Figure 2 shows that the improvement held for all 3 subjects and all 3 critical frame durations. Further analyses showed that there were two types of errors made at close spatial separations, namely, identifying a neighboring letter instead of the target and (2) failure to identify either the target or the neighbor accurately. Errors were more frequent when the pair of targets fell within a single hemisphere.

These novel results show that there is a limit on how much information can be processed in any local region during a single attentional glimpse, i.e., processing at one location is enhanced by 'borrowing' resources from nearby regions. At a neural level, such adjustments in processing resources may be caused by changes in neural firing rates, or changes in receptive field tuning. Optimal visual performance would be achieved by designing displays in which important features are widely-spaced. (Bahcall and Kowler, 1995).

(c) Saccadic accuracy and precision: These experiments investigated the pooling process that brings the line of sight to spatially-extended targets. Unlike the studies on spatial filtering described above, the stimulus was a single target and the instruction was to look at the target as a whole, rather than to aim for a specific place within it. The main result was that saccadic accuracy and precision were quite good. With small, single point targets average landing positions missed the target by only 1% of eccentricity with standard deviations of saccadic landing position only 6% of the eccentricity. This level of precision is comparable to that of relative perceptual localization. This high level of performance was maintained even for very large targets (up to 3 deg diam at an eccentricity of 4 deg). Precision was impaired for larger targets. The independence from target size suggests that a pooling mechanism operates on spatially-extended targets to determine a precise landing position without adding much noise to the computation. The landing position is sufficiently precise that it is now possible to do experiments the manipulate target configuration so as to understand how the pooling process works. (Kowler and Blaser, 1995).

(d) Saccades to dot clusters: The pooling process that guides saccades to spatially-extended targets was investigated by studying saccades made to 4 deg diam clusters of 19 random dots (Fig. 3). Random dot clusters were studied in order for us to study sensory aspects of the spatial pooling process with minimal interference from deliberate strategies of saccadic guidance. Any such strategies would not be too effective with random dot targets because the location of the center of gravity of the patterns was not obvious in eccentric vision, nor could it be inferred from previously

presented targets. Eye movements were recorded via a Dual Purkinje Eyetracker (noise < 1') while subjects were instructed to make a single saccade, as accurately as possible, to the dot cluster. Instructions were to aim at the cluster as a whole rather than at a specific place within it.

The main finding was that saccades landed at reliable places within the pattern. The landing position was near but not precisely at the center-of-gravity. Slopes of the functions relating saccadic landing position to center-of-gravity (Fig. 4a,b) were less than 1 and the variability of saccades (after center-of-gravity was taken into account) was only 10% of eccentricity (larger than the variability of saccades to single point targets). Correlations of saccadic landing position with the presence of a dot at any display location showed that dots from the entire display were taken into account in determining the landing position of the saccade. Assigning differential weights to different portions of the cluster did not improve the prediction of saccadic landing position, indicating dots all contributed regardless of whether they were located near the center or the boundary, and regardless of their eccentricity. Varying dot intensity over a log unit did matter, with the bright dots influencing landing position about twice as much as the dimmer dots.

These results show that the spatial pooling process computes with unexpectedly high precision a central landing position within unstructured spatially-extended targets. The observed departures of this landing position from the center of gravity were not due differential weighting of dot locations. We suspect that such departures were caused by processes subsequent to the center of gravity computation involved with transforming the visual error signal into the saccadic command. The results also show that the pooling process was sensitive to local characteristics of the pattern, thus ruling out models based on low-pass filtering. It is more likely that pooling operates by averaging the local signs of units sensitive to different portions of the pattern, with the contribution of each unit determined by the number and intensity of the dots in its receptive field. One would expect that increasing the number of such units should increase the spatial precision of the saccade, but this did not happen: saccades to 4 deg diameter targets are less precise than saccades to single points. A good explanation for this loss of precision with larger targets is that the receptive field size (and, hence, the spatial precision) of the units involved becomes larger when the stimulus is larger. Thus, it may not be possible for the visual system to spatially pool the output of units with small receptive fields over too wide an area. (McGowan, Kowler and Sharma).

<u>(e) Saccades to spatially-filtered targets:</u> The spatial pooling process is being investigated by studying the precision of saccades directed to Gabor patches (sinusoidal gratings whose contrast is modulated by a Gaussian envelope). The main objective is

to find out whether saccades use the same set of spatial filters as the perceptual system, or whether some spatial frequencies, although visible, constitute ineffective (i.e., noisy) targets for saccades. Results show that saccades are insensitive to spatial frequency and to contrast, once stimuli reach threshold. (McGowan, Kowler, Bergen and Lubin.)

(f) Saccades to targets of different shapes: Theories of form perception have given a prominent role to the "medial axis" of forms (Blum, 1974) and recent psychophysical data (Kovacs and Julesz, 1994) suggest that the medial axis may indeed be computed by units that pool information across the contour. We studied saccades to forms in which the medial axis and center of gravity were in different locations. Saccadic landing position favored the medial axis and saccadic precision was independent of the shape. Follow up experiments will study landing positions to shapes during performance of a "real" tasks (e.g., memorize the shapes; compare the shapes to find out which one is different). We want to find out whether the demonstrated capacity of the saccadic system for precise localization is used during these tasks, or whether it sets an upper bound on performance which far exceeds the demands made by even difficult perceptual tasks. The latter outcome indicates that the perceptual and cognitive systems would have considerable flexibility in determining landing position unimpaired by sensorimotor noise. (Melcher and Kowler).

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Undergraduate students:

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*Eric Anderson
Dorothy Nesmith
Erik Blaser

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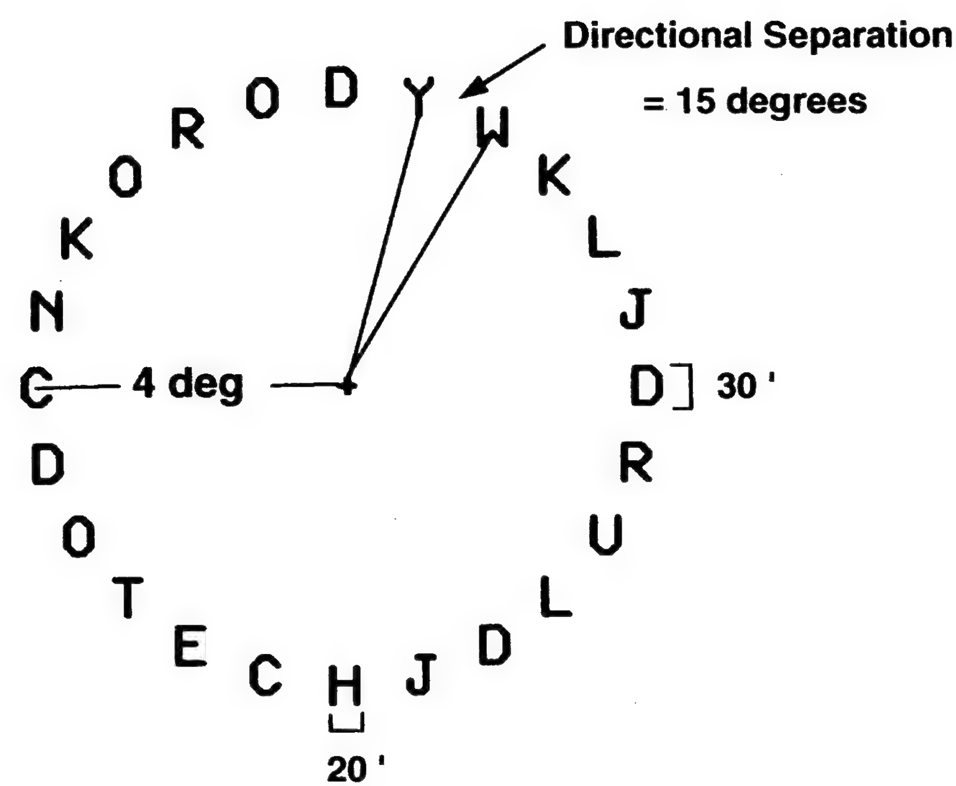
Fig 1A



Directional Separation
= 15 degrees
D Y W K L J D R U L D J H C E T O D C N K O R O
4 deg
30 '
20 '

Fig 1 B

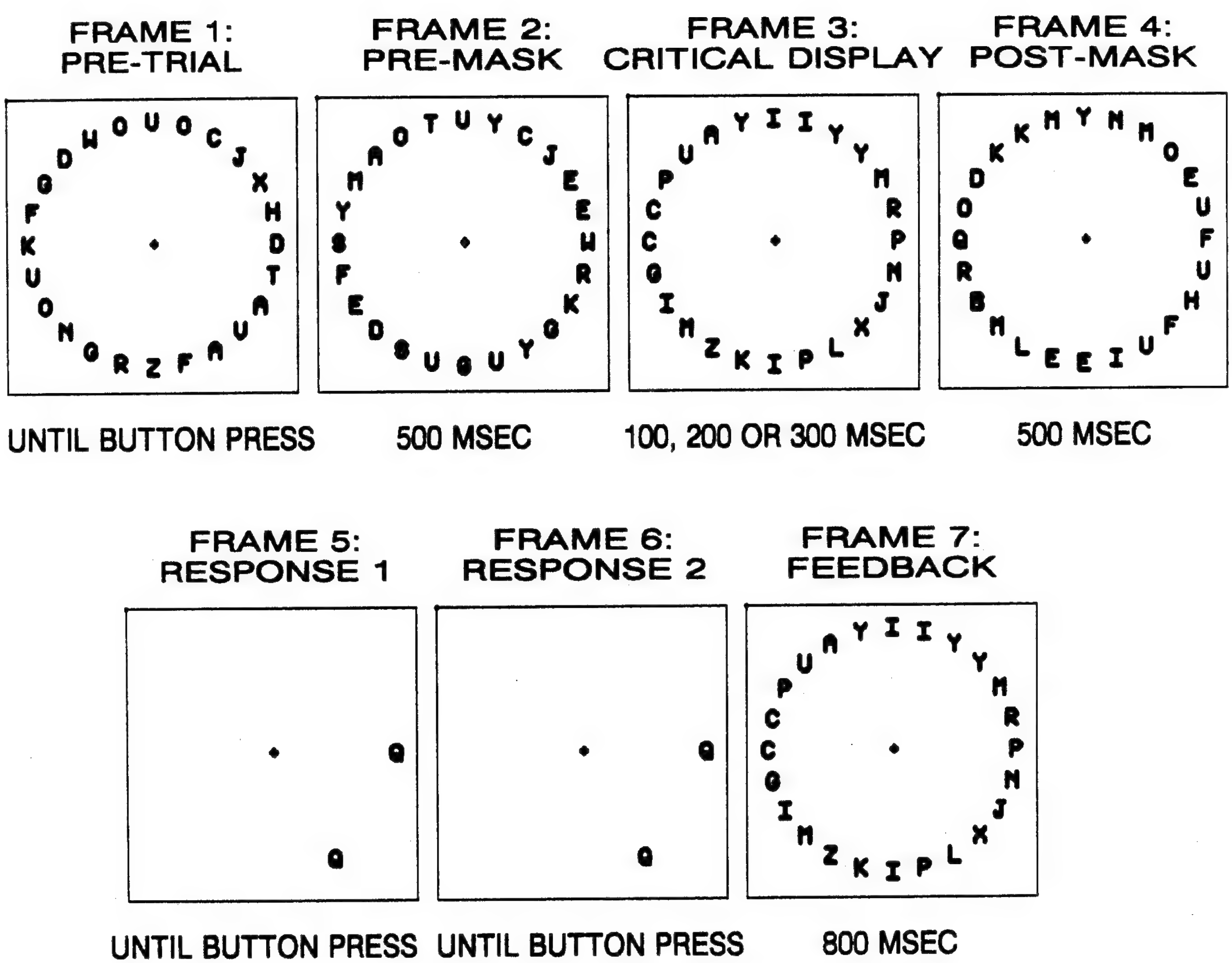

FRAME 1:
PRE-TRIAL
FRAME 2:
PRE-MASK
FRAME 3:
CRITICAL DISPLAY
FRAME 4:
POST-MASK
UNTIL BUTTON PRESS
500 MSEC
100, 200 OR 300 MSEC
500 MSEC
FRAME 5:
RESPONSE 1
FRAME 6:
RESPONSE 2
FRAME 7:
FEEDBACK
UNTIL BUTTON PRESS
UNTIL BUTTON PRESS
800 MSEC

Fig 2

Percent of trials with two correct responses

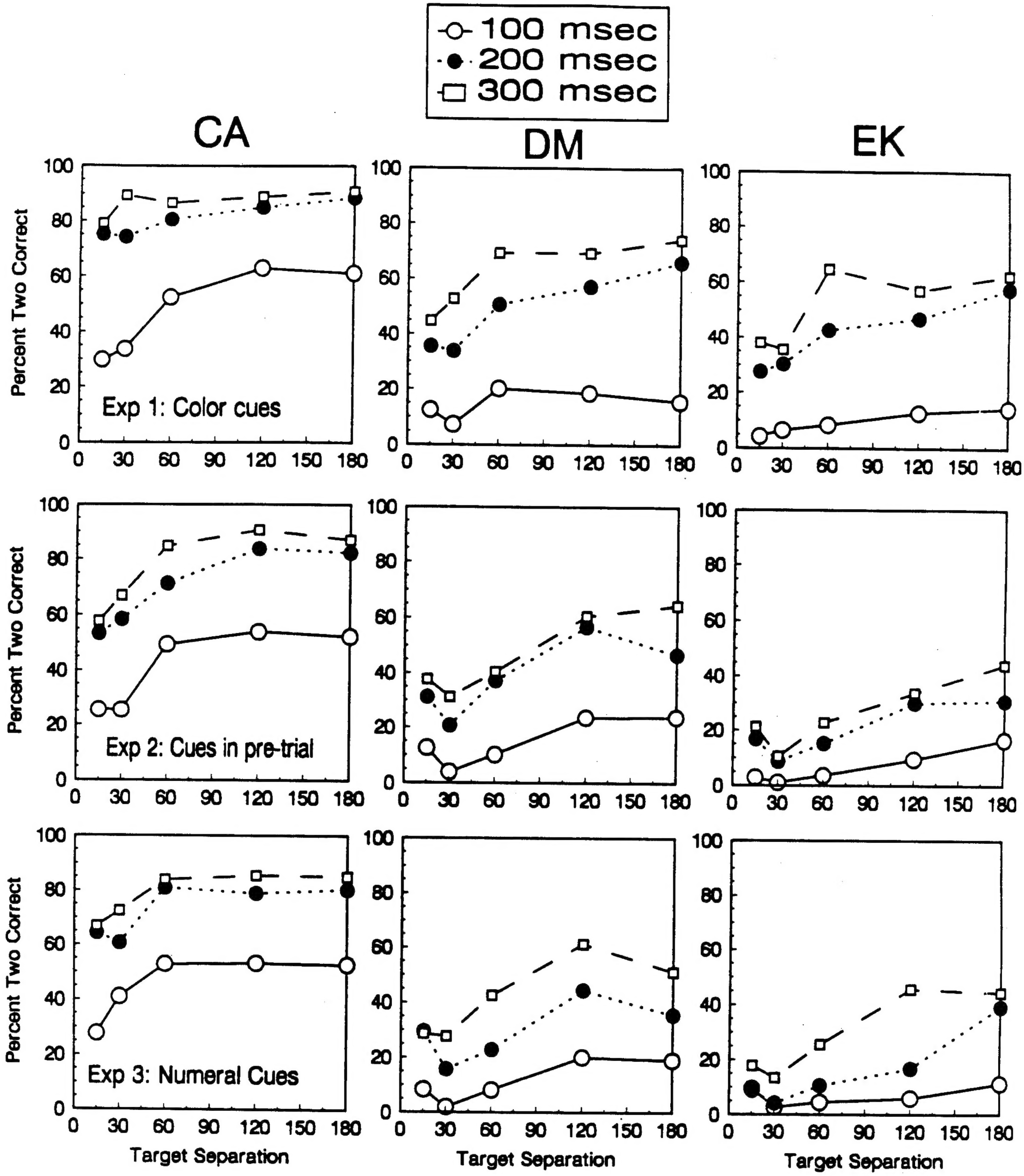


Fig 3

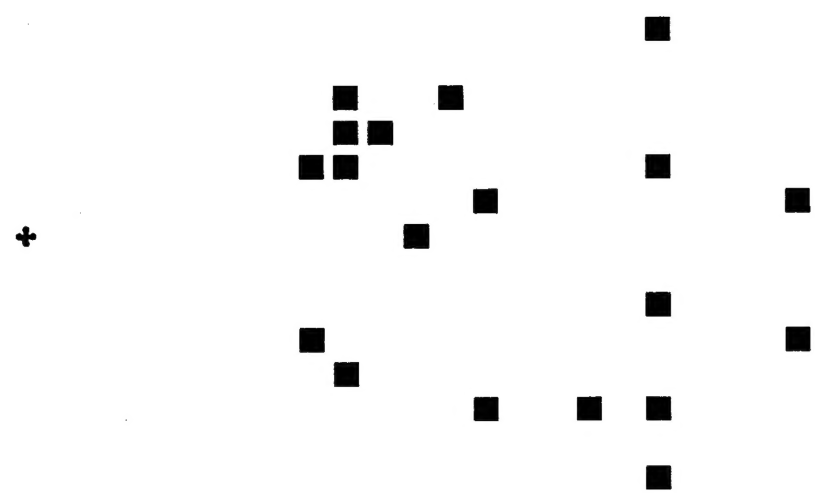
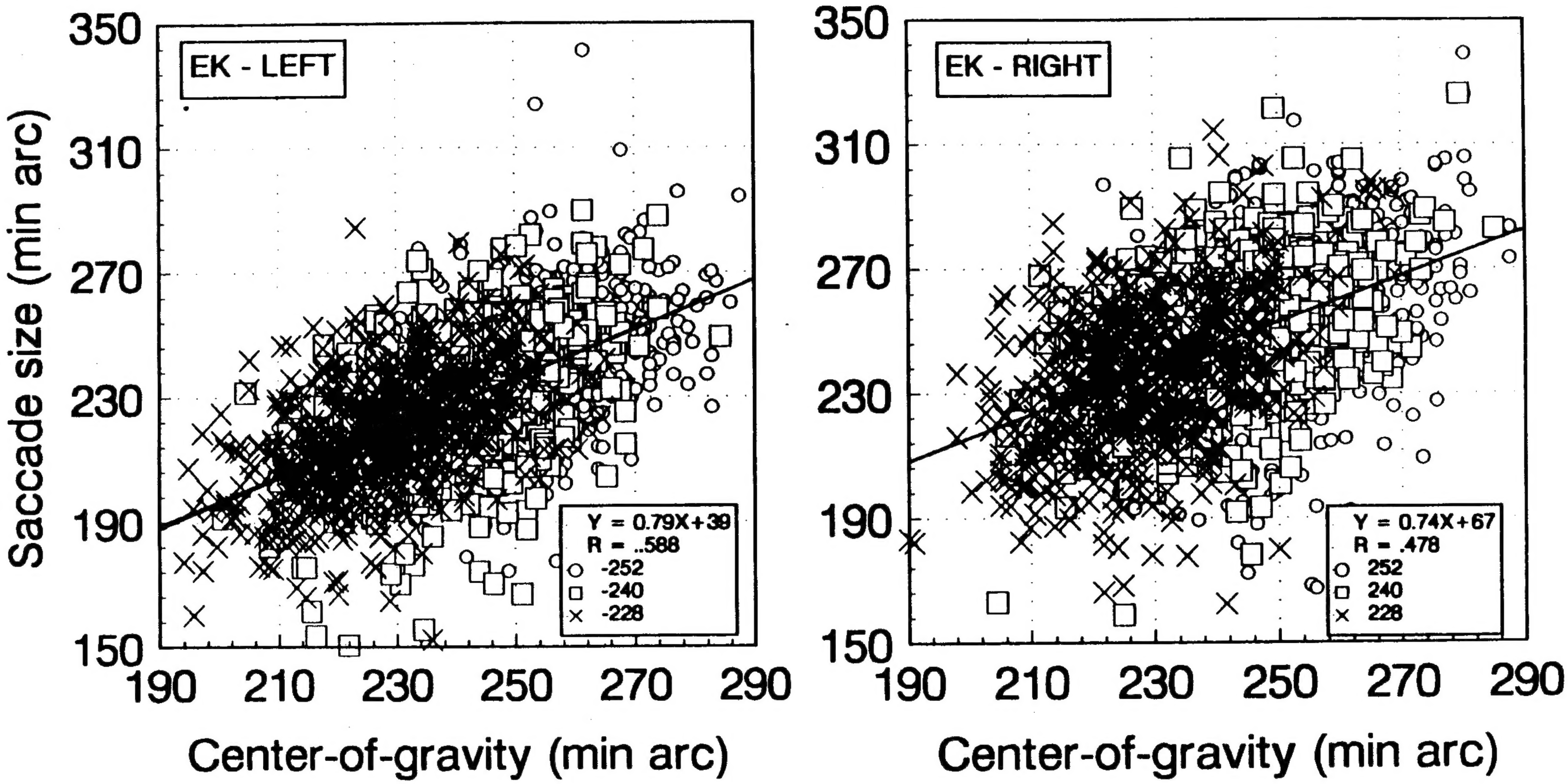
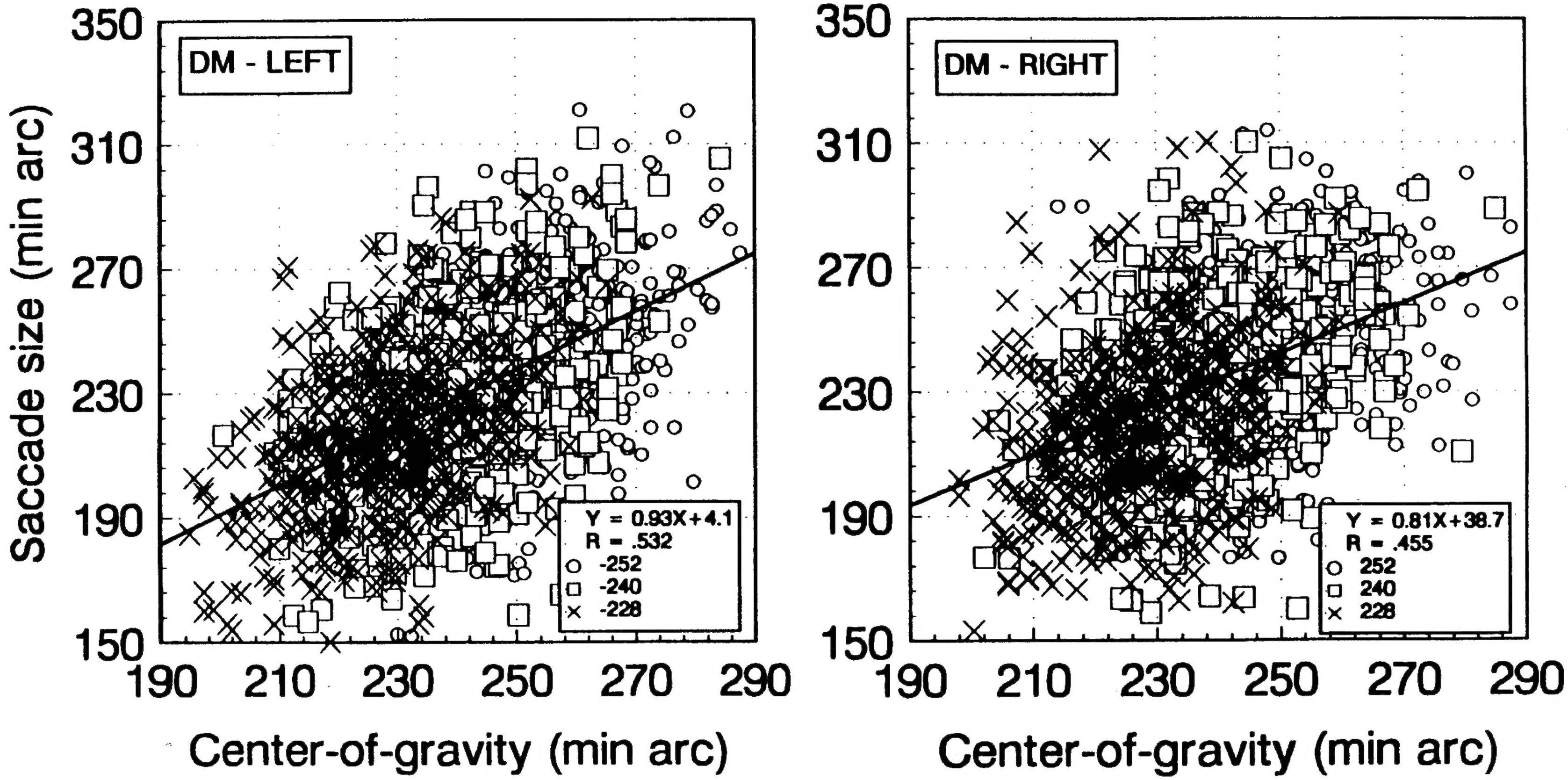


Fig 4 A



EK - LEFT
Y = 0.79X+39
R = ..588
-252
-240
-228
EK - RIGHT
Y = 0.74X+67
R = .478
252
240
228
Saccade size (min arc)
Center-of-gravity (min arc)
350
310
270
230
190
150
190
210
230
250
270
290

Fig 4B



DM - LEFT
Y = 0.93X+4.1
R = .532
-252
-240
-228
DM - RIGHT
Y = 0.81X+38.7
R = .455
252
240
228
Saccade size (min arc)
350
310
270
230
190
150
190
210
230
250
270
290
Center-of-gravity (min arc)
Center-of-gravity (min arc)